APPLICATION OF MATHEMATICAL MODELING FOR THE UNIFICATION OF THE PRODUCTION OF METALLURGICAL ENTERPRISES ON THE EXAMPLE OF TUBING

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Abstract
The article is devoted to topical issues of resource saving and application of modern systems of engineering analysis for forecasting the properties of products of metallurgical enterprises. The article discusses the problems of interchangeability of cast-iron tubing used in the mining industry for the lining of mines and tunnels. On the example of the VC60 alloy product, a mathematical model was proposed that allows to unify this type of product while maintaining the required quality indicators. The analysis of the safety factor of tubing, both with changes in the design of the stiffener and without them, using the finite element method (FEM) and the program of mathematical modeling SAE module SolidWorks Simulation. The constructed diagrams and the results of stress state calculations showed that the design of universal tubing, with additional fixing holes in the stiffener, will not yield to the standard reliability by reliability. Based on the conducted research and analysis of international quality standards, the authors consider the possibility of eliminating ten separate tube sizes and the commissioning of one type of tubing, but of universal design.

Keywords: high-strength cast iron, safety factor, tubing, finite-element method

1 Introduction

To date, a special role in the development of the Russian economy is played by the mining industry. In the sector of enterprises of this industry, a large number of labor, financial, natural, material, energy and production resources are concentrated. At the same time, the quality of products used in this area must meet certain standards and meet certain quality requirements.

The most responsible design used in the mining industry is the system of the cast-iron lining of tunnels. This construction is a cylindrical tube consisting of successively assembled rings of the same type and size. Each ring consists of box-section segments - tubing, which is connected with each other and with adjacent rings by bolts. The breakdown of the lining ring into components (tubing) is largely subordinated to the convenience of assembly and movement. The main dimensions of the tubing are determined on the basis of constructive and industrial considerations. The size is limited to 160-190 cm so that the weight of one element does not exceed 1.0-1.5 tons [1].

Priority in the work of metallurgical enterprises is the high quality of the products with a simultaneous implementation of a flexible pricing policy, focusing on the interests of consumers.

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For one mine a customer requires 10 varieties of tubing made of high-strength cast iron VCH60 with a wall thickness of 90 mm. The difference between individual types of tubing is the location of holes on the stiffening rib.
Since all the holes are obtained by casting, each type of tubing requires the production of a separate accessory. For costs reason it is profitable to produce one universal type of tubing, but not ten separate types. In this case, it is necessary to provide for 11 holes on the stiffening rib instead of standard 2-3 holes (**Fig. 1**). For such a decision it is necessary to calculate the safety factor of tubing with additional holes and without them.

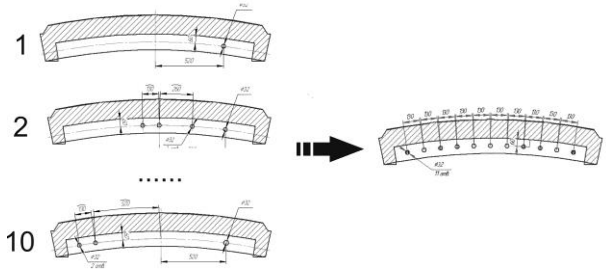

Fig. 1 Layout diagram of the holes on the tubing stiffening rib

According to the GOST R 57054-2016 adopted in September 2016 for specific mining conditions, it is allowed to produce tubing with other parameters that must be coordinated with the bodies of Rostechnadzor [2]. In order to make a decision on making changes to the design of the tubing, it is required to obtain new characteristics of the parts and make sure that the new products meet the requirements for the quality of the products and have the declared characteristics of the customer.
Given the complex production process, many product profiles, stringent customer requirements, rationalization or restructuring of production are closely related to scientific and technological improvement and scientific research. Any innovations in production are quite expensive, therefore at the first stage of research, it is customary to apply mathematical modeling.
Existing software systems basically contain equations that allow you to calculate, under given conditions, the characteristics of the research object. The results of calculations can be checked for contradictions in the conditions and criteria, and also estimate the degree of error.
One of the main problems of applying mathematical modeling in scientific developments is the lack of a sufficient number of staff able to realize the potential of software for adapting programs to a certain type of production.
In order to assess how much additional holes affect the reliability of the variable stiffener, the program is able to construct the safety factor variation diagrams along the section of the stiffener with additional holes and without them.
For more detailed analysis, the safety factor can be calculated at individual points of the stiffener section, in accordance with the requirements of the product from the customer.
In general, the application of mathematical modeling programs can have a certain effect on the growth and introduction of innovations in industry, but one should remember a number of conditions for using them:

1. competent task setting before the designer;
2. the operator (the designer) should be able to use and adapt the task to the conditions of production;

3. conducting an assessment of the adequacy of the constructed model;
4. the need for practical confirmation in the laboratory complex with the construction of a real model.

2 Experimental material(s) and methods

In order to calculate in SolidWorks Simulation, it is necessary to determine the properties of the material, which the tubing is made of, and to set the border conditions. According to the technical documentation, tubing is made of high-strength cast iron VCH60. According to the customer's data the operating temperature range for this tubing is 0 to +20 ◦C. Therefore, for the calculation we took the following mechanical properties of the material [3]:

Modulus of elasticity – 180000 MPa;
Poisson's ratio – 0.22;
Tensile strength – 600 MPa;
Compressive strength – 600 MPa;
Yield limit – 370 MPa;
Density – 7200 kg/m^3.

Border conditions:

To perform the calculation in SolidWorks Simulation, it is necessary to specify the conditions of fixing of the product and determine the load influencing on the product.

1. Conditions of the product fixation. We assumed that the tubing is securely fixed to the mounting holes (6 holes on each flank surface)
2. External loads. Under the terms of stress condition of the tubing provided by the customer, the tubing must accommodate the normal force of 3817334 N. Under the terms of the calculation the force was normally directed to the outer surface of the tubing.

SolidWorks Simulation, a commonly known CAE module, was used in order to calculate the safety factor. CAE (Eng. Computer-aided engineering) – a common name for programs designed for engineering calculations of designs and analysis of the processes related to them [2].

Calculations performed in SolidWorks Simulation are based on the finite-element method [1]. The finite-element method (FEM) is a numerical method for solving differential equations with partial derivatives, as well as integral equations arising in the solution of applied physics tasks. The essence of the FEM is that the studied area is divided into finite elements, a type of approximating function is randomly selected in each of the elements, and then values of these functions are evaluated at the boundaries of the elements. The process of dividing the model into small pieces is the creation of the grid.

To determine the safety factor of tubing in SolidWorks Simulation a static analysis was performed. Application of this method of calculation is possible under the following conditions [1]:

Assumption of linearity

The resulting response is directly proportional to the applied load. For example, if we double the load rate, the response of model (of displacement, load, and stress) will also double. The assumption of linearity can be used if the following conditions are met:

- The calculated highest pressure takes place in the linear part of the stress-strain diagram that starts with a straight line emanating from the origin of coordinates.
- The maximum calculated displacement is significantly smaller than the characteristic size of a part. For example, the maximum displacement of the plate must be

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significantly smaller than its thickness, and the maximum displacement of the beam must be significantly smaller than its cross-section.

The assumption of elasticity:
When removing the load, the part recovers its original shape (no permanent deformation).
The assumption of static:
Loads are applied slowly and gradually until they reach their full values. Abrupt application of loads causes additional displacements, loads, and stresses.
For comparison, modeling load distribution was used to determine the safety factor of tubing without holes on the stiffener and tubing with eleven holes (**Figs. 2, 3**).

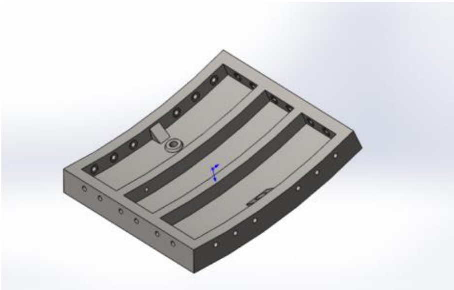

Fig. 2 Tubing without holes

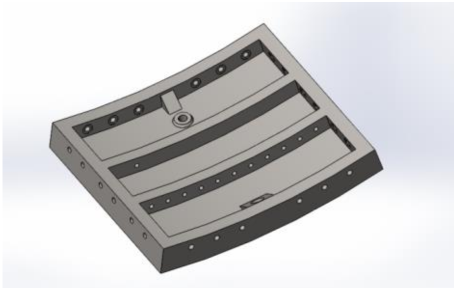

Fig. 3 Tubing with additional holes

For the purpose of calculations, a tetragonal grid without holes for the tubing with additional holes was generated.
To determine the safety factor SolidWorks Simulation uses the criterion of the maximum design voltage [2]. This criterion specifies that the material starts to deform when the maximum equivalent stress reaches the yield limit of the material. The yield limit is defined as the property of the material. To calculate the equivalent stresses in SolidWorks Simulation, several techniques were included (von Mises stress, Mohr-Coulomb stress, the maximum normal stress, etc.).
Since the cast iron is a material with a brittle fracture mode, the Mohr-Coulomb criterion was used in order to determine the safety factor of the tubing [4].
The criterion of the Mohr-Coulomb stress is based on the theory known as the theory of internal friction. The theory forecasts the occurrence of a failure, if for the combination of maximum and minimum of the principal stress the appropriate limits of stress were exceeded [1].
For the calculated stresses σ_1, σ_2 and σ_3, which are ordered as $|\sigma_1| > |\sigma_2| > |\sigma_3|$, the Mohr-Coulomb theory forecasts failures in accordance with **Tab.1** [1].

Table 1 Forecasting failures in accordance with the theory of Mohr-Coulomb [1]

Principal stresses condition	Failure criterion	FOS
Both principal stresses under tension: $\sigma_1 > 0$ and $\sigma_3 > 0$	$\sigma_1 > \sigma_{Extension\ Limit}$	$(\sigma_1/\sigma\sigma_{Extension\ Limit})^{-1}$
Both principal stresses under compression:	$\lvert\sigma_1\rvert > \sigma_{Compression\ Limit}$	$(\lvert\sigma_1\rvert / \sigma_{Compression\ Limit})^{-1}$

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Principal stresses condition	Failure criterion	FOS
$\sigma_1 > 0$ and $\sigma_3 > 0$		
$\sigma_1 > 0$ under tension, $\sigma_3 < 0$under compression	$\sigma_1 / \sigma_{\text{Extension Limit}} + \lvert\sigma_3\rvert / \sigma_{\text{Compression Limit}} > 1$	$(\sigma_1 / \sigma\sigma_{\text{Extension Limit}} + \lvert\sigma_3\rvert / \sigma_{\text{Compression Limit}})^{-1}$
$\sigma_1 < 0$under compression, $\sigma_3 > 0$ under tension	$\lvert\sigma_1\rvert / \sigma_{\text{Compression Limit}} + \sigma_3 / \sigma\sigma_{\text{Extension Limit}} > 1$	$(\lvert\sigma_1\rvert / \sigma_{\text{Compression Limit}} + \sigma_3 / \sigma\sigma_{\text{Extension Limit}}$

The yield limit of cast iron was used in the calculations as $\sigma_{\text{Extension Limit}}$ и$\sigma_{\text{Compression Limit}}$.

3 Discussion of calculation results

According to the results of calculation in SolidWorks Simulation curves of safety factors were built, **Figs. 4 - 7**.

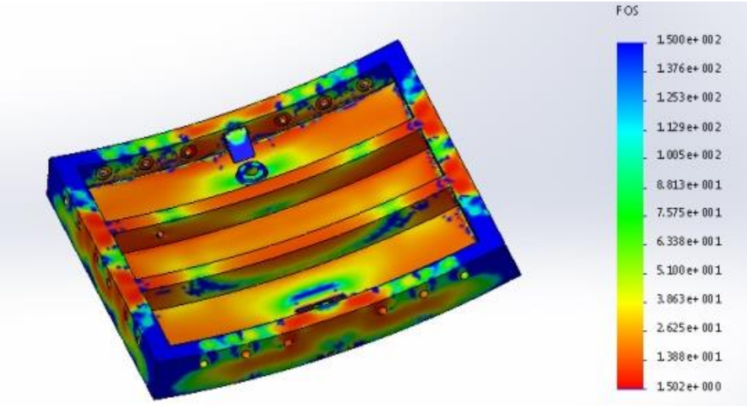

Fig. 4 Curves of safety factors of the tubing without holes (inside)

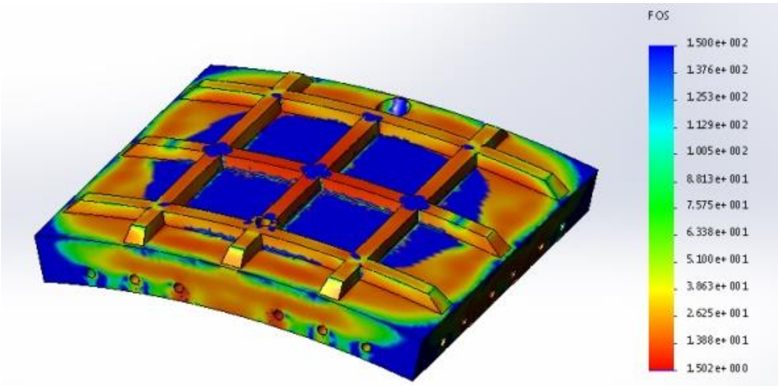

Fig. 5 Curves of safety factors of the tubing without holes (outside)

The meaning of the safety factor may be interpreted as follows [4]:

- The safety factor of less than 1.0 in any location indicates that the material in that location passed to the yield state and the design became unreliable.

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- The safety factor equal to 1.0 in any location indicates that the material in that location started to pass to the yield state.
- The safety factor over 1.0 in any location indicates that the material in that location is not compliant yet.

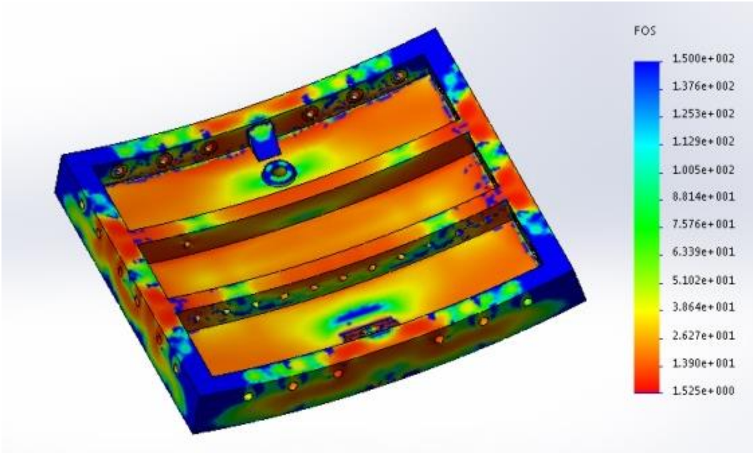

Fig. 6 Curves of safety factors of the tubing with additional holes(inside)

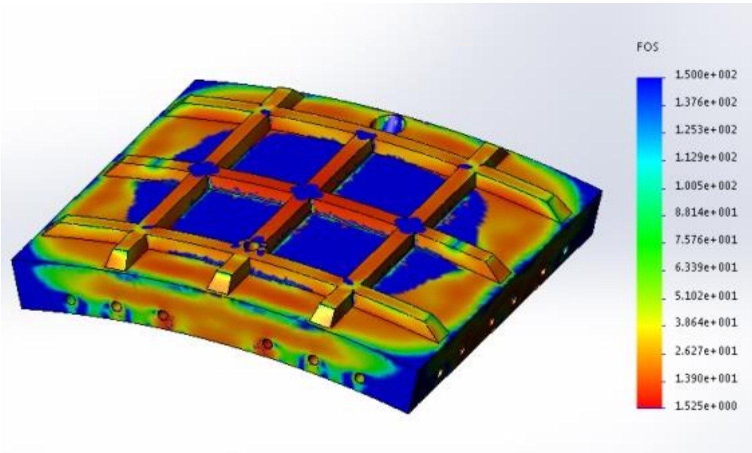

Fig. 7 Curves of safety factors of the tubing with additional holes (outside)

The material in any location will start to become yielding if you apply new loads equal to the current loads multiplied by the resulting safety factor.
Calculations show that the tubing without holes and tubing with additional holes have the same minimum safety factor of 1.5 (**Figs. 8, 9**).
The minimum safety factor of a product in both cases corresponds to the areas of tubing located near the mounting holes. Thus, regardless of the tubing design, the maximum stresses develop in the same parts of the product.

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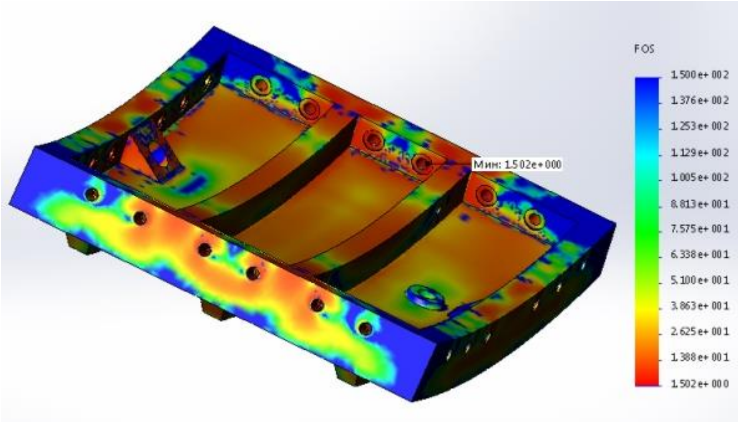

Fig. 8 Minimum safety factor of tubing without holes

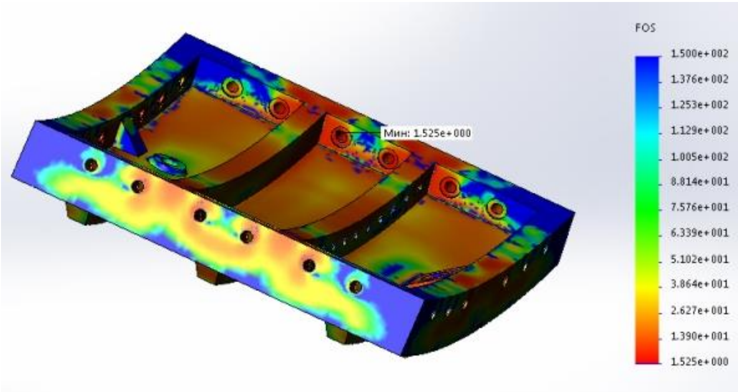

Fig. 9 Minimum safety factor of tubing with additional holes

In order to estimate to what extent the additional holes affect the reliability of the variable stiffening rib the change in the safety factor in the cross section of stiffening rib with additional holes or without them was analyzed (**Figs. 10 - 11**).

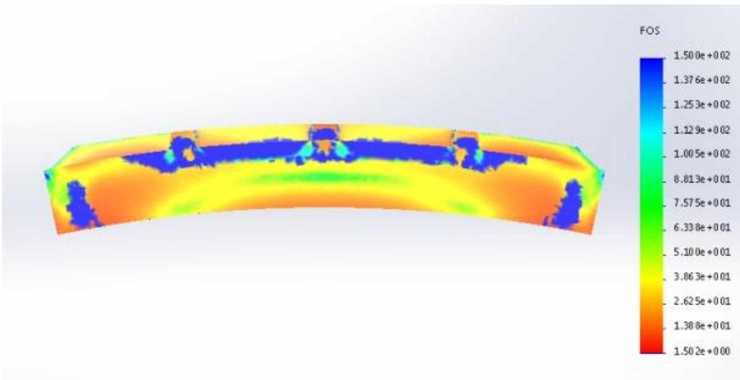

Fig. 10 Curve of changes in the safety factor in the changed stiffening rib cross section without holes

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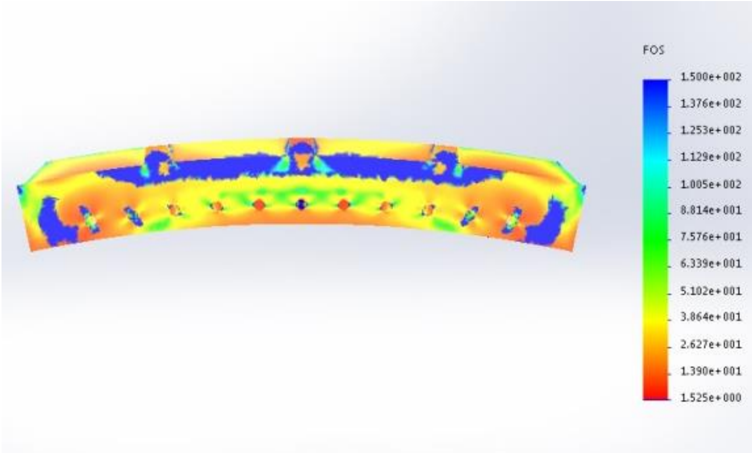

Fig. 11 Curve of changes in the safety factor in the changed stiffening rib cross section with additional holes

For more detailed research the safety factor was calculated in the individual points of the stiffening rib cross section according to the diagram (**Fig. 8**). The calculation results in points corresponding to **Fig. 12** are shown in **Fig. 13**, **Fig. 14**, **Fig. 15**.

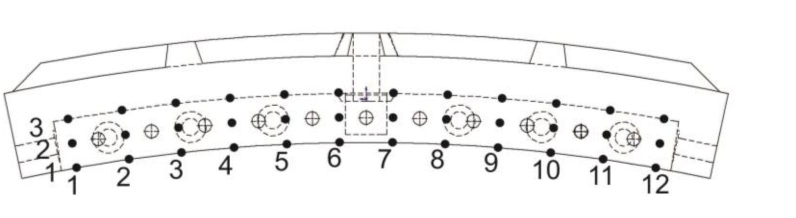

Fig. 12 Diagram for determining the safety factor in the stiffening rib cross section

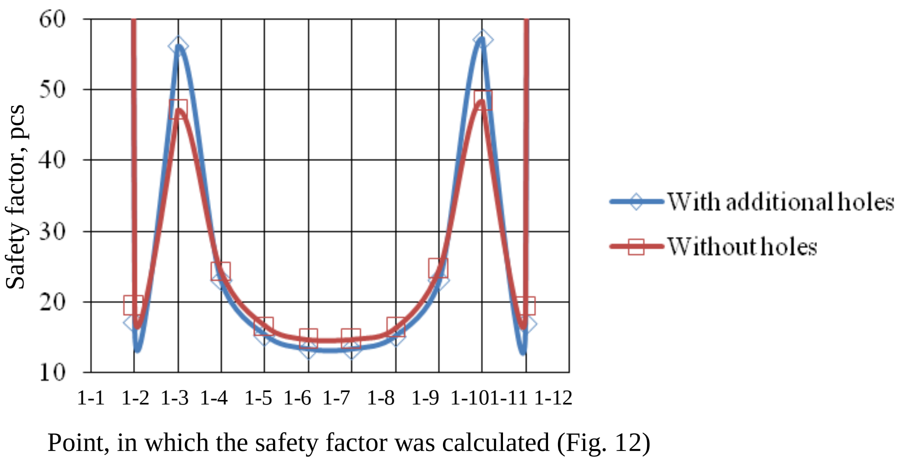

Fig. 13 Change in the safety factor in the stiffening rib cross section

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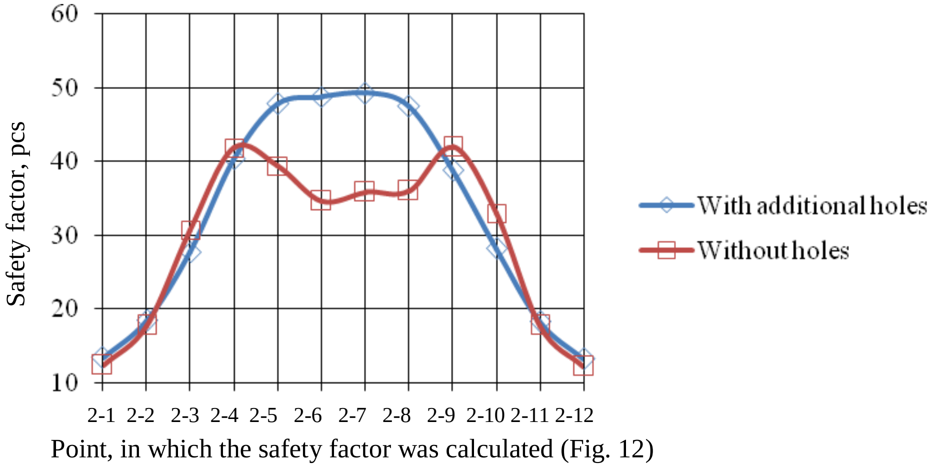

Fig. 14 Change in the safety factor in the stiffening rib cross section

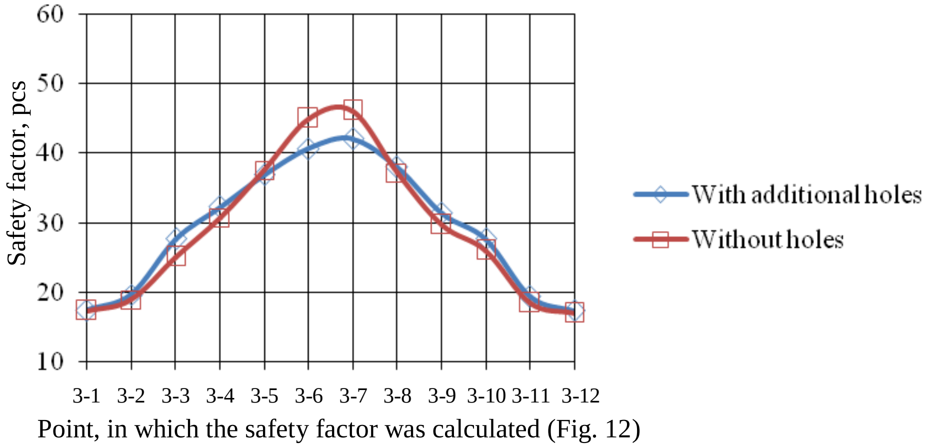

Fig. 15 Change in the safety factor in the stiffening rib cross section

It follows from the obtained dependences that the maximum loss of the safety factor in the stiffening rib cross section upon the occurrence of additional holes amounted to 15%. Provided the stiffening rib safety factor ranges from 10 to 60, the loss of the safety factor of 15% can be considered acceptable for this design.

4 Conclusion

The results of the stress state calculations showed that the loss of the safety factor of the new universal tubing design, with additional fixing holes in the stiffener, would be 15%. Thus, the new design for reliability will not significantly yield to the standard ones. As for the economic and rational assessment of the need for the proposed changes, it is necessary to take into account the requirements of international quality standards and the national standard for the manufacture of GOST R 57054-2016, as well as requirements for the performance characteristics of customers and conduct a detailed study of the physical model for modeling compliance with real conditions.

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